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Original article

Economic and CO_2 avoided emissions analysis of WWTP biogas recovery and its use in a small power plant in Brazil

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A B S T R A C T

An anaerobic wastewater treatment generates at the end of its process an anaerobic biomass, also known as anaerobic sludge, and a major sub product, the biogas, composed mainly by methane (CH_4) and carbonic gas (CO_2). The biogas needs to be collected in order to be flared or used in another process, especially because it cannot be released directly into the atmosphere due to methane gas and its high global warming potential. Nevertheless, when this gas is burnt, an energy vector for micro generation is discarded. In the present work was designed a thermal power plant using the biogas produced in an anaerobic wastewater treatment plant (WWTP) through an implementation methodology that considers the population growth according to a southeast ordinary Brazilian city. The energy production potential, avoided CO_2 emissions due to the biogas burnt and the possibility of using this energy to supply the WWTP's internal demand consumption were analyzed, as well as the project's economic viability and the arising benefits from carbon credits, calculated in three scenarios. The data of calculus were based on the Brazilian sales tariffs obtained from Brazilian National Electric Energy Agency – ANEEL, where: i) T1 = 64.9 [US$/MWh] (average tariff on Brazilian energy auction A-5); ii) T2 = 86.47 [US$/MWh] (average tariff for thermal power plants in the same auction), and iii) the third scenario, in which the energy produced would be consumed by the WWTP's internal demand. The economic viability was only achieved in second and third scenarios, being intensified in the scenario that WWTP's internal demand is supplied using the energy generated in the biogas plant.

Introduction

Anaerobic systems for wastewater treatment are those that occurs in oxygen absence along the process, conducted in anaerobic reactors, such as: i) UASB (Up flow Anaerobic Sludge Blanket Digestion) Reactor or ii) Upward Flow Anaerobic Filter. According to Nuvolari [27], they are less efficient (from 60 up to 70%) than aerobic systems. However, the implementation and operation costs are lower, often being employed before the aerobic treatments.

Abbasi and Abbasi [1] states that the compactness of UASB reactors, their lower operational costs and sludge production make this technology very attractive. Recent research are also pointing to the possibility of hydrogen production on these reactors [30,26].

Nowadays, emissions and carbon footprint of water treatment utilities are an important issue. Therefore, the opportunities for reducing it in either small or large wastewater treatment plants needs to be considered. The use of anaerobic rather than aerobic treatment processes achieve this aim due to no aeration requirements and generation of methane to be used in the plant (Chong, 2012).

Municipal wastewater is a potential source of chemical energy [15]. According to Campos [7], the anaerobic treatment results in anaerobic biomass formation, also known as anaerobic sludge, and biogas, a major by-product of the organic matter processed, mainly composed of methane (CH_4) and carbon dioxide (CO_2). The substantial importance of this fuel is because it does not have

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geographic limits in its production, and the technology of production is not monopolistic either [38].

The biogas obtained from anaerobic digestion plants (AD-plants) can be used directly to produce steam, electricity, vehicle fuels and chemicals as well. Moreover, is possible to purify it in order to increase methane concentration, by removing CO_2 and other impurities, for substitution of natural gas in the existent distribution grid [36]. Costa [11] *apud* CENBIO [8] stated that biogas energy conversion presents an alternative use to the large volume of waste produced, and reduces the toxic potential of methane emissions while simultaneously produces electricity, culminating in environmental gains and costs savings due to the lower energy purchasing from the local dealership.

Salomon and Lora [32] also quotes the advantages of producing electricity from biogas, considering decentralized and renewable generation close to the consuming sites and the possibility of using cogeneration processes.

Maghanaki et al. [22] stated that anaerobic digestion biogas is one of the renewable energy sources that in addition to energy production has the ability to produce fertilizers, increasing public health levels, being useful for diseases control thereby creating a good solution for solid waste disposal. According to the same author, the global biogas capacity will reach 22,000 MW by 2025. In 1993 that production in Latin America was estimated at 217 million m^3 per year [25], which has certainly increased within the two last decades due the greater waste generation rate. In this context, energy generation ventures from biogas produced in sewage treatment plants can contribute to the development of the biogas potential in a region. For example, in Portugal, only the potential of the energy generation by wastewater treatment plants is near to 0.15 [TWh/year] [2] *apud* [16], demonstrating the potential for energy generation from wastewater. In Brazil, Santos et al. [35] estimated that the maximum potential of Brazilian generation, in anaerobic wastewater treatment plants could reach 1 TWh in 2040, representing nearly 0.3% of Brazilian's residual fuel consumption, showing that this generation option should not be neglected.

The Biogas quality changes according to its source due to residues characteristics. The amount and quality of material used in its production has a significant effect on concentrations of different trace compounds in biogas, affecting his methane percentage and energy potential. Biogas composition variations are usually low in sewage digester because of the usually steadier process conditions [31]. The siloxanes presence is an example of the compounds that could hamper energy production and impose damages to the plant equipment [13].

It is known that the population growth, even moderated, increases the wastewater generation, especially in Brazil, where sewage treatment rate has considerably increased, implying in a high potential for biogas generation and consequently energy production. The last data from National Sanitation Information System – SNIS [37] presented a growth of some indicators, such as: Percentage of wastewater collected and urban wastewater treated, from 60.2 to 60.8% and from 53.5 to 55.5% between 2010 and 2011, respectively. As the effluent flow is continuous, power generation is also and can be considered a renewable source that collaborates to decrease fossil fuels consumption and Greenhouse Gases emissions (GHG). As stated by Mason et al. [21], the increase in electricity generation from renewable sources is the key to the urgent and necessary GHG emissions reduction into the atmosphere.

In this context, this paper aims to design a plant for energy recovery in a wastewater treatment plant (WWTP) for a Brazilian city, using a methodology that considers population growth. The potential for energy production, the possible use of this energy in the WWTP's internal demand and its economic viability were also evaluated, as well as the benefits of carbon credits calculated in three scenarios for sale tariffs and energy use.

Methodology

For the purpose of this dimensioning was used data from the population of an ordinary city in the state of Minas Gerais – Brazil, as these cities have increasingly shown significant issues and rising economies. The thermal power plant fueled by biogas was sized considering a lifespan of 25 years, starting its operations in 2015 and the biogas production in 2016 until 2041. The historical series of population size used for projection purposes were obtained from the Brazilian Institute of Geography and Statistics [18] and is presented on Table 1.

The population projection was performed using the logistic model, as presented by Qasin [29] and also applied by Barros [4] and Von Sperling [42]. This model allows the prediction of a population by using the Eq. (1):

$$P(t) = \frac{Ks}{1 + e^{-a(t-t0)}} \tag{1}$$

where the coefficients a, c, e, Ks are calculated in the Eqs. (2)–(4) below:

$$Ks = \frac{2 \cdot P0 \cdot P1 \cdot P2 - P1^2(P0 + P2)}{P0 \cdot P2 - P1^2} \tag{2}$$

$$a = \frac{1}{t_2 - t_1} \cdot \ln\left[\frac{P0(Ks - P1)}{P1(Ks - P0)}\right] \tag{3}$$

$$c = \frac{Ks}{P0} - 1 \tag{4}$$

where P0, P1 and P2 refer to the population's data of the three years considered. It is emphasized that, in Eq. (2), the population must comply with the restriction $P1^2 \neq PO \cdot P2$.

Methane production was calculated from Eq. (5), presented by Chernicharo [10] based on reduction of organic load effluent converted in CH_4, expressed in terms of chemical oxygen demand (COD):

$$Q_{CH4} = Q_{Sewage} \cdot \frac{[S_0(1 - Y) - S]}{f(T)} \tag{5}$$

where:

- Q_{CH4} = Methane flow produced [m^3/day];
- Q_{sewage} = Sewage flow to the reactor [m^3/day];
- Y = Solid production coefficient;
- S_0 = Affluent COD concentration;
- S = COD concentration effluent [kgCOD/m^3];
- $f(T)$ = Volumetric conversion and temperature correction factor.

The factor $f(T)$ is calculated from Eq. (6), obtained from Chernicharo [10]. Atmospheric pressure (1 atm) and average environmental temperature of 298 K were taken into account. The constants K and R refer to COD, which corresponds to 1 mol of CH_4 (64 g COD/mol) and the universal gas constant (0.08206 atm. l/mol.K) [10].

$$f(T) = \frac{PK}{RT} \tag{6}$$

Table 1
Populations data.

Year	Inhabitants
1991	85,606
2000	98,322
2010	109,783